# Search for Higgs boson pair production via $\gamma\gamma WW^*(\to l\nu jj)$ with the ATLAS detector

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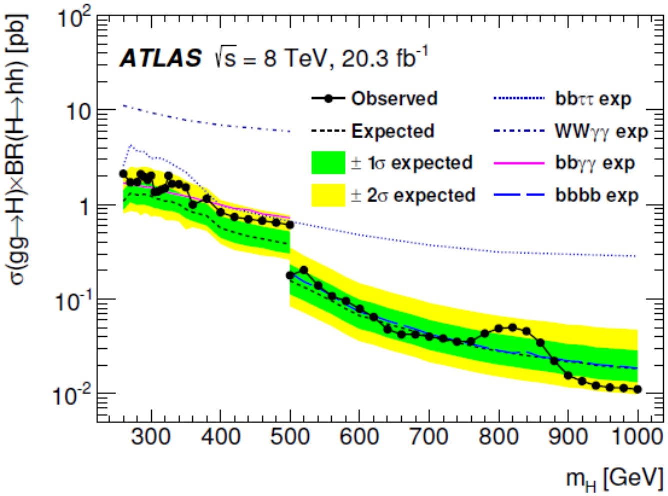
CLHCP 2017

Nanjing University, Nanjing

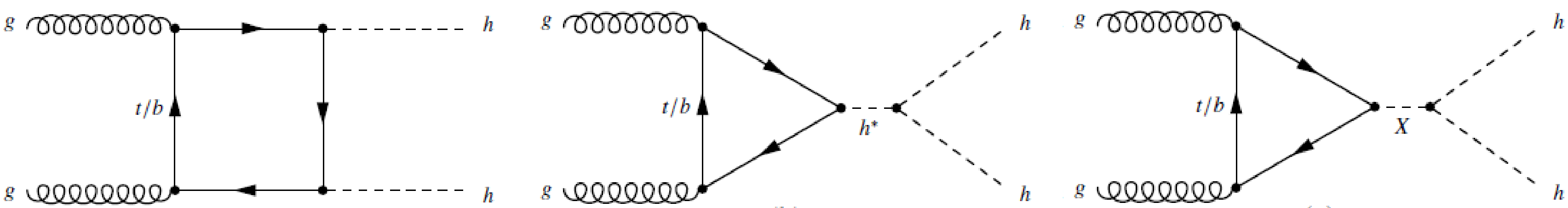
December 22-24, 2017

# Introduction

- Higgs pair production has a small XS in SM (~33 fb @ 13 TeV) with triangle and box destructive interference.
- BSM can effectively enhance Higgs pair production.
  - ✓ non-resonance: altered Higgs self-coupling or ttH coupling. [Fig. (a) and (b)]
  - ✓ resonance: BSM resonance decay, such as heavy Higgs and Kaluza-Klein graviton. [Fig. (c)]
- This has been extensively searched with $hh \to bb\gamma\gamma, bbbb,\ bb\tau\tau$ and $WW\gamma\gamma$ in RUN Ⅰ and $hh \to bb\gamma\gamma,\ bbbb,\ bbWW,\ WWWW,\ bb\tau\tau$ and $WW\gamma\gamma$ in RUN Ⅱ




Phys. Rev. D 92, 092004 (2015)



(a) (b) (c)

# Overview

- Search for Higgs pair with $WW\gamma\gamma \rightarrow jjl\nu\gamma\gamma$
  - ✓ Benefit from a large BR from $h \rightarrow WW$ and a clean signature from $h \rightarrow \gamma\gamma$
- Signals
  - ✓ non-resonant, SM Higgs pair model
  - ✓ resonance in low mass region (260, 300, 400, 500 GeV), gg->X->hh, Spin0 with narrow decay width

- Share the same selections in non-resonant and resonant searches
- Counting experiment

- ATLAS-COM-CONF-2016-072

# Object definitions

**Photons**

Two well identified and isolated photons with the following $p_T$ and $m_{\gamma\gamma}$ selections:

$\frac{p_T(\gamma 1)}{m(\gamma\gamma)} \geq 0.35$, $\frac{p_T(\gamma 2)}{m(\gamma\gamma)} \geq 0.25$;

$m(\gamma\gamma) \in [105, 160]$ GeV.

**Electrons**

$p_T > 10$ GeV;

$|\eta| \in [0, 1.37] \cup [1.52, 2.47]$;

$|d_0|/\sigma(d_0) < 5$; $|z_0| < 0.5$ mm;

Identification: Medium;

Isolation: Loose criteria.

**Jets**

Anti-kt jets with R = 0.4;

$p_T > 25$ GeV; $|y| < 2.5$;

Jet Vertex tagging algorithm (JVT) used to suppress the pileup jets;

$JVT$ scores $< 0.59$ & $p_T < 60$ GeV & $|\eta| < 2.4$ .

**Muons:**

$p_T > 10$ GeV; $|\eta| \in [0, 2.7]$;

$|d_0|/\sigma(d_0) < 3$; $|z_0| < 0.5$ mm;

Identification: Medium;

Isolation: GradientLoose criteria;

# Event selection

- Start with the selections aiming at identifying $h \rightarrow \gamma\gamma$ events
- At least two central jets
- B-Veto (Working Point: 70%)
- At least one lepton
- Tight miss window (TMW), $\left|m_{\gamma\gamma} - 125.09\right| < 2 \times 1.7\ (\sigma_{m_{\gamma\gamma}})$ GeV

- [SR] Signal Region (above)
- [SB] Sideband Region (reverse “Tight Mass Window”)
- [CR] Control Region (reverse “Tight Mass Window” & $\mathrm{N(lepton)} = 0$ )

# Background estimations

- SM Higgs background is estimated with MC.

- Continuum background is estimated with data-driven method.

$$N_{SR}^{continuum} = N_{SB}^{continuum} \times \frac{\epsilon_{\gamma\gamma}}{1-\epsilon_{\gamma\gamma}}$$

$\epsilon_{\gamma\gamma}$ is extracted from CR ($N_{lep} = 0$) with a fit.

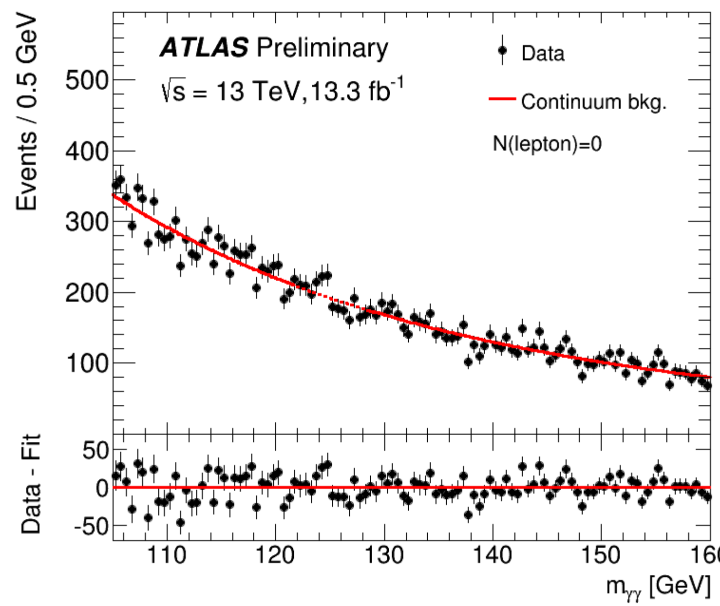
$$\epsilon_{\gamma\gamma} = \frac{\int_{TMW} f(m_{\gamma\gamma}) dm_{\gamma\gamma}}{\int_{105}^{160} f(m_{\gamma\gamma}) dm_{\gamma\gamma}},$$

$f(\mathrm{m}_{\gamma\gamma}) \rightarrow$ fit function: exponential with 2nd order polynomial

# Continuum background

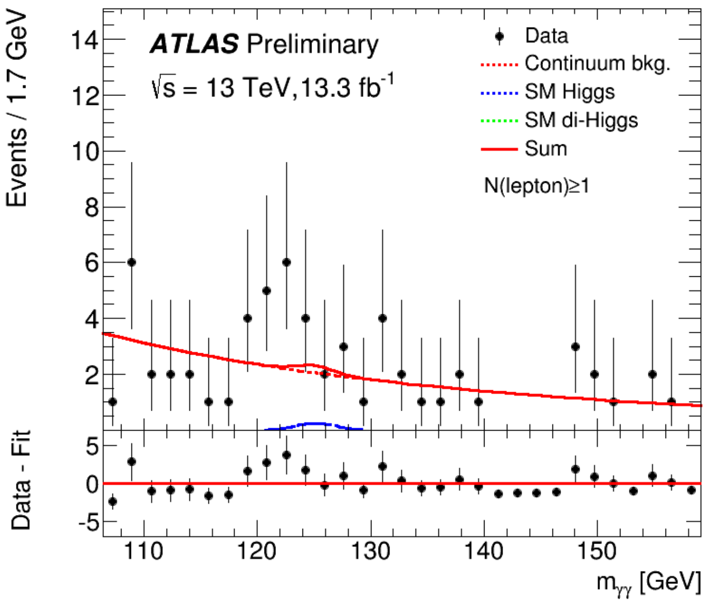
- $\epsilon_{\gamma\gamma}$ is measured in zero-lepton control region with data
- The exponential with 2nd order polynomial is used to model background

$N_{SB}^{continuum} = 46$ events
$\epsilon_{\gamma\gamma} = 13.64\%$
$N_{bkg}^{continuum} = 7.26$ events



# Summary of event yields

| Process | Number of events | |
|---|---|---|
| Continuum background | 7.26 | ± 1.23 |
| SM single-Higgs | 0.616 | ± 0.115 |
| SM di-Higgs | 0.0187 | ± 0.00224 |
| Observed | 15 | |




- The events within the TMW are listed in the table
- 15 events observed in the signal region, about 8 events for background
- No significant excess

# Systematic uncertainties (1)

- The uncertainties related to the continuum background.

- Statistical uncertainty of events (27) in sideband: **14.7%**.

- The uncertainties on $\epsilon_{\gamma\gamma}$ measurement
  - ✓ From lepton multiplicity: 7.4%,
  - ✓ From fitting functions: 3.8%,
  - ✓ From sideband definition: 1.2%,
  - ✓ From statistics (using 10k toys): 1.3%.

# Systematic uncertainties (2)

- Luminosity error, 2.9%, combining errors on luminosity in 2015 and 2016

- Theoretical uncertainties
  - ✓ $+2.1/2.0\%$ on branching ratio of $h \to \gamma\gamma$ and $\pm$1.5% on $h \to WW$.
  - ✓ Scale and PDF uncertainties on $\sigma(gg \to hh)$ and cross section of SM Higgs processes.
  - ✓ 37.5% assigned to Wh process for jet multiplicity, comparing Pythia8 (parton shower jets ) and MadGraph5 (matrix element jets) both with 2 jets inclusively.

- Experimental uncertainties:
  - ✓ Pileup reweighting, photons, jets, leptons, b-tagging

# Systematic (3)

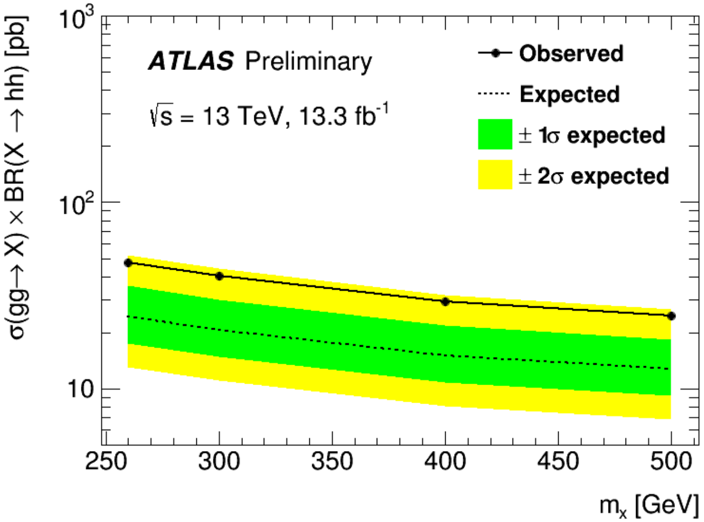
| Source of uncertainties | | Non-resonant $hh$ | $X \to hh$ | Single-$h$ bkg | Cont. bkg |
|---|---|---|---|---|---|
| | | All numbers are in % | | | |
| Luminosity 2015+2016 | | 2.9 | 2.9 | 2.9 | - |
| Trigger | | 0.4 | 0.4 | 0.4 | - |
| Pileup re-weighting | | 0.8 | 0.2 | 1.8 | - |
| Event statistics | | 2.0 | 1.8 | 2.7 | 14.7 |
| Photon | energy resolution | 2.0 | 1.8 | 1.2 | - |
| | energy scale | 4.2 | 4.1 | 1.6 | - |
| | identification | 4.2 | 4.2 | 4.2 | - |
| | isolation | 1.0 | 1.0 | 1.1 | - |
| Jet | energy resolution | 0.8 | 0.2 | 8.0 | - |
| | energy scale | 3.5 | 3.5 | 5.2 | - |
| $b$-tagging | $b$-jets | 0.06 | 0.05 | 5.4 | - |
| | $c$-jets | 0.5 | 0.5 | 0.3 | - |
| | light jets | 0.4 | 0.4 | 0.4 | - |
| | extrapolation | 0.006 | 0.06 | 0.8 | - |
| Lepton | electron | 0.7 | 0.7 | 0.7 | - |
| | muon | 0.3 | 0.3 | 0.6 | - |
| $\epsilon_{\gamma\gamma}$ | lepton dependence | - | - | - | 7.4 |
| | background modelling | - | - | - | 3.8 |
| | sideband definition | - | - | - | 1.2 |
| | statistics on $\epsilon_{\gamma\gamma}$ | - | - | - | 1.3 |
| Theory | PDF | (2.1) | - | 2.2 | - |
| | $\alpha_S$ | (2.3) | - | 1.5 | - |
| | scale | (6.0) | - | 3.7 | - |
| | HEFT | (5.0) | - | - | - |
| | jet multiplicity | - | - | 12.5 | - |
| | BR($h \to \gamma\gamma$) | 2.1 | 2.1 | 2.1 | - |
| | BR($h \to WW^*$) | 1.5 | 1.5 | 1.5 | - |
| Total | | 12.0 | 8.4 | 18.6 | 17.0 |

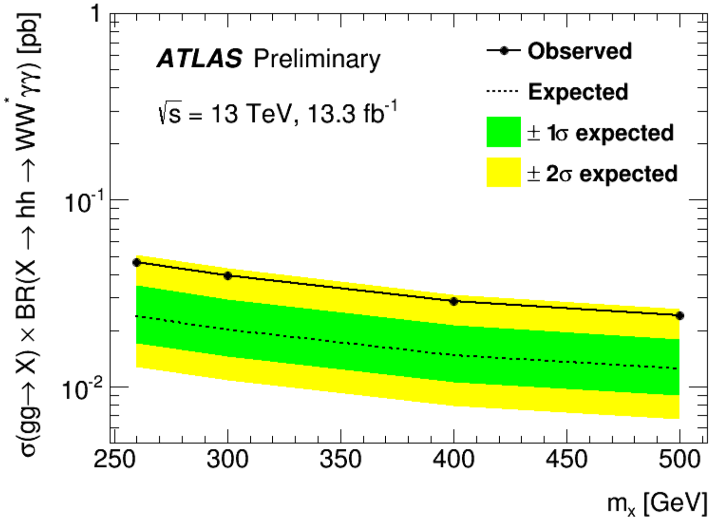
# Expected upper limits

**The 95% CL upper limits have set.**

**Histfactory is used to build up the statistical model for an event-counting experiment.**

**Asymptotic approximation is used (was validated with throwing toys MCs).**
**In the non-resonant search, the expected limit is 12.9 pb, and the observed one is 25.0 pb. For resonant search, the observed limit ranges from 47.7 pb to 24.7 pb and the expected limit ranges from 24.3 pb to 12.7 pb.**



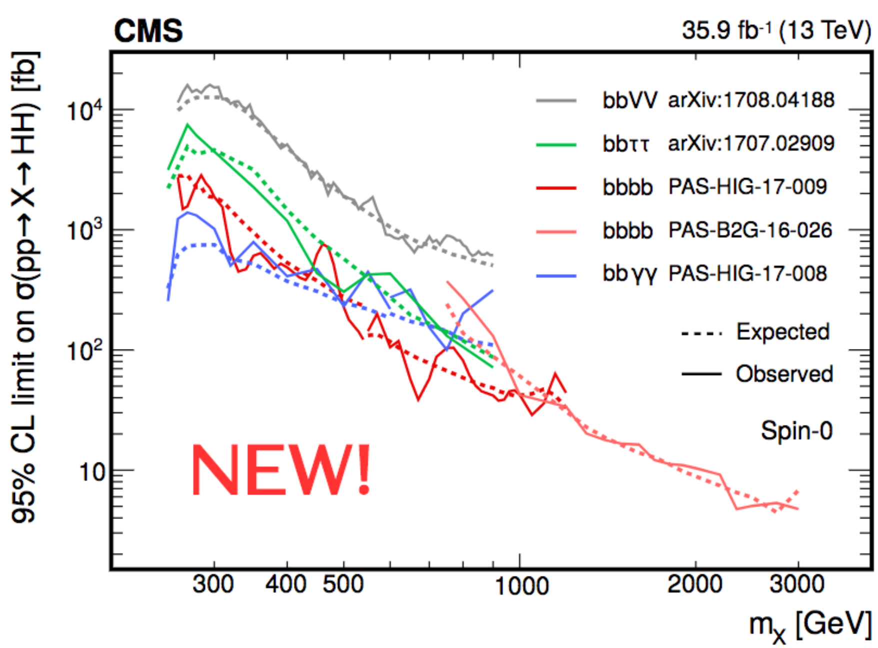



# CMS result

Limits on the resonance

$\sigma_{gg\to X} \times Br_{X\to hh}$ < 1 pb (300 GeV)

< 4 fb (3 TeV)




Obs. (exp) limit on the $\sigma_{hh}/\sigma_{SM}$

| Channel | CMS | ATLAS |
|---|---|---|
| $b\bar{b}\gamma\gamma$ | 19 (16) | 177 (162) |
| $b\bar{b}\tau\tau$ | 30 (25) | |
| $b\bar{b}b\bar{b}$ | 342 (308) | 29 (38) |
| $b\bar{b}WW^*$ | 79 (308) | |
| $\gamma\gamma WW^*$ | | 750 (386) |

2.3 – 3.2 fb-1

13.3 fb-1

35.9 fb-1

# Summary

- **No significant excess is observed with respect to the SM background-only hypothesis.**

- **The 95% confidence-level upper limit have set.**

  - ✓ **For non-resonant production, the observed limit on cross section is 25.0 pb and expected limit is 12.9 pb.**
  - ✓ **For resonant production, the observed limit on the resonant production times the branching fraction of $X \rightarrow hh$ ranges from 47.7 pb to 24.7 pb and the expected limit ranges from 24.3 pb to 12.7 pb.**

- **The analysis with more data (36.1 fb-1) is ongoing. The result will be combined with other channels and will be interpreted to the specific models.**

# Backup

# $\epsilon_{\gamma\gamma}$ measurement (1)

Test against different lepton multiplicities with MC to quantify the impact on $\epsilon_{\gamma\gamma}$.
MC $jjl\nu\gamma\gamma$ and $jj\gamma\gamma$ are compared.
The difference on the $\epsilon_{\gamma\gamma}$ is 2.2%.

Test against different lepton multiplicities with data control regions to quantify the impact on $\epsilon_{\gamma\gamma}$.
As the MC samples have high diphoton purity, $\epsilon_{\gamma\gamma}$ has been measured with regions by inverting either the photon isolation or the photon identification to check the impact of lepton multiplicities.
The difference on the $\epsilon_{\gamma\gamma}$ is 7.4% and considered as one of uncertainties conservatively introduced by lepton multiplicities.

Test against different sideband region definitions to quantify the impact on $\epsilon_{\gamma\gamma}$.
The difference (1.2%) on $\epsilon_{\gamma\gamma}$ between nominal definition and varied one is considered as one of uncertainties introduced by the SB definition.

# $\epsilon_{\gamma\gamma}$ measurement (2)

- Test against various fitting functions of background modeling to quantify the impact on $\epsilon_{\gamma\gamma}$.
- Fitting functions: 0 order polynomial, $1^{st}$-order polynomial, $2^{nd}$-order polynomial, exponential.

- The largest difference on $\epsilon_{\gamma\gamma}$ to the nominal is taken as uncertainty except comparing the 0 order polynomial due to this function is improper to fit the $m_{\gamma\gamma}$ shape.

- The difference between the 1st order polynomial and nominal fit model is 3.8% and is considered as uncertainty introduced by the choice of fitting functions.